Core Ideas:

1. Herbicide-resistant Palmer amaranth is a major pest in cropping systems in the U.S.
2. Integrated weed management tactics are needed to delay further resistance issues.
3. Cover crops and PRE herbicides reduced Palmer amaranth exposure to dicamba 98%.
4. Replacing a third POST with a layby reduced exposure to dicamba by 38,319 plants ha^{-1}.
5. Cotton yield was highest when utilizing a cover crop and preemergence herbicides.

Cover crops, residual herbicides, and application method reduce selection pressure to dicamba POST potentially delaying Palmer amaranth resistance

Lavesta C. Hand[1], Taylor M. Randell[1], Robert L. Nichols[2], Lawrence E. Steckel[3], and A. Stanley Culpepper[4]

[1]Graduate Research Assistant, Department of Crop and Soil Sciences, University of Georgia, Tifton, GA, USA; [2]Senior Director of Agronomy, Weed Control, Nematology, and Pathology, Cotton Incorporated, Cary, NC, USA; [3]Professor, Department of Plant Sciences, Jackson, TN, USA; [4]Professor, Department of Crop and Soil Science, University of Georgia, Tifton, GA, USA.

Author for correspondence: Lavesta C. Hand, Graduate Research Assistant, University of Georgia, Coastal Plains Research Station, 2360 Rainwater Road, NESPAL Building, Tifton, GA 31794. (Email: camphand@uga.edu)

ABSTRACT

Dicamba-tolerant soybean (*Glycine max* L.) and cotton (*Gossypium hirsutum* L.) are the most common herbicide-tolerant technologies planted for these crops across the U.S.; thus, measures to reduce selection for dicamba-resistance in weeds is paramount. Four studies in GA and TN evaluated the potential for integrated strategies to reduce selection pressure on dicamba applied POST in cotton. A split-plot arrangement consisted of conventional tillage or rye cover crop as the whole plot. The subplot included four herbicide systems: no herbicide, 3 sequential POSTs, PRE fb 3 POSTs, and PRE fb 2 POSTs fb LPD. Each POST application was glyphosate plus dicamba. The cover crop reduced Palmer amaranth (*Amaranthus palmeri* S. Watson) density 75, 70, and 54% at POST 1, POST 2, and POST 3 applications, respectively. PRE herbicides reduced densities 99, 99, and 96% at the aforementioned application timings, respectively, while a combination of cover crop plus PRE herbicides resulted in similar reductions. Cumulative for the season, Palmer amaranth exposure to dicamba was reduced 65% by cover crops, 98% by PRE herbicides, and 98% by cover crop plus PRE herbicides. Replacing the third POST with an LPD application further reduced plants exposed with dicamba by 38,319 plants ha^{-1}. Crowfootgrass (*Dactyloctenium aegyptium* (L.) Willd.) and yellow nutsedge (*Cyperus esculentus* L.) followed trends observed with Palmer amaranth. Neither cover crop nor PRE herbicides effectively reduced the number of pitted morningglory (*Ipomoea lacunosa* L.) controlled by glyphosate plus dicamba POST. Also of significance, no program completely eliminated weeds at harvest, early-season cotton heights in total POST programs were reduced at least 27% by early-season weed competition, and cotton yields were greater when using conservation tillage systems.

Abbreviations: POST, postemergence; PRE, preemergence; LPD, layby post-directed; fb, followed by.

INTRODUCTION

Problematic weeds are constantly adapting to agricultural practices (Culpepper, 2006; McElroy, 2014; Webster and Nichols, 2012). One of the earliest recorded examples of this phenomenon was the ability of a weed species to evolve and appear similar to the cultivated crop, resulting in the inability of hand laborers to distinguish the weed from the crop visually (McElroy, 2014). Weed management strategies have seen a dramatic shift from primarily physical weed control to chemical weed control in the developed world (McElroy, 2014; Ziska et al., 2019); yet, weeds continue to adapt by evolving resistance to herbicidal mechanisms of action (Busi et al., 2013; Green and Owen, 2011; Gressel et al., 2016).

The selection of herbicide resistant weeds is a function of species biology, characteristics of genes conferring herbicide resistance, and the number of individuals treated over time and space (Gaines et al., 2019; Heap, 2014). Glyphosate-resistant crops were commercialized in 1996, resulting in a rapid shift to heavy reliance on glyphosate for weed control in some of the most widely produced crops in the U.S., such as cotton (*Gossypium hirsutum* L.) and soybean (*Glycine max* L.) (Green, 2009; Jones and Snipes, 1999; Young, 2006). Immediately following the introduction of glyphosate resistant varieties, the number of different mechanisms of action utilized in soybean during the growing season rapidly decreased from five to just one – glyphosate (Young, 2006). Although some scientists believed that weed resistance to glyphosate was extremely unlikely, as soon as five years after the introduction of this technology, glyphosate resistant weeds had become problematic in many production systems (Bradshaw et al., 1997; VanGessel et al., 2001; Culpepper et al., 2006). In the case of glyphosate-resistant weeds, initial mutation frequency was low; however, glyphosate was used over a large area, with broad-spectrum activity selecting for many resistant biotypes (Gaines et al., 2019; Heap, 2014).

This, coupled with the abandonment of other effective weed control practices including herbicide rotation and cultural or physical control methods, led to widespread herbicide resistance in many crops.

Following the selection for widespread glyphosate resistance in weeds, both industry and academic scientists recommended the reincorporation of integrated weed management strategies, such as utilization of residual herbicides or implementing tillage (Gustafson, 2008; Sosnoskie and Culpepper, 2014). Although residual herbicides are important components to weed management programs in a multitude of crops, postemergence (POST) herbicide applications are still necessary for adequate weed control (Everman et al., 2009; Johnson et al., 2012). To provide greater flexibility to growers as well as increase POST herbicide options, cotton has been engineered with resistance to POST applications of glufosinate, 2,4-D, and dicamba (Meyer et al., 2015; Cahoon et al., 2015; Manuchehri et al., 2017). These Xtendflex™ varieties accounted for nearly 55% of the cotton varieties planted in the U.S. during 2019, while approximately 65 to 75% percent of soybean varieties planted during that time had the Xtend™ trait package providing resistance to glyphosate and dicamba (USDA AMS, 2019; E. Prostko, personal communication). These traits are widely planted because they provide flexibility in weed control and have high yield potential; as a result, dicamba use has increased. Dicamba was applied on less than 10% of hectares planted to cotton in 2010 compared to 43% of planted cotton hectares in 2019, while less than 1% of planted soybean hectares received dicamba in 2012 compared to 27% in 2018 (USDA NASS, 2020). Dicamba-based weed management programs can effectively control many of the most problematic weeds in the U.S. including Palmer amaranth (*Amaranthus palmeri* S. Watson), common waterhemp (*Amaranthus tuberculatus* (Moq.) J. D. Sauer), horseweed (*Conyza canadensis* L.), giant ragweed (*Ambrosia trifida* L.), and morningglory species (*Ipomea* spp.) (Barnett et al., 2013; Kruger et al., 2010; Leon et al., 2016; Meyer et al., 2015).

Although dicamba-based herbicide systems can be effective, rapid adoption and overreliance on dicamba applied POST is already of great concern in regards to weed resistance development. Greenhouse studies have shown that Palmer amaranth exposed to sublethal rates of dicamba for three generations can lead to populations with reduced sensitivity (Tehranchian et al., 2017). As a result of overreliance on dicamba in corn and wheat production, there are populations of dicamba resistant kochia (*Bassia scoparia* (L.) A.J. Scott) in the Midwest (Cranston et al., 2001). Additionally, just four years after the introduction of dicamba-tolerant crops, dicamba resistant Palmer amaranth has been identified in Tennessee (Steckel, 2020). To delay the likelihood of resistance in other populations, integrated approaches such as utilizing multiple effective herbicide mechanisms of action and cultural control methods must be utilized.

Applying multiple mechanisms of action as a tank mixture is a method to reduce selection pressure and potentially improve weed control (Green et al., 2016; Vann et al., 2017). Crops tolerant to both glufosinate and dicamba would allow for an effective dicamba POST tank mixture that can improve weed control beyond either herbicide applied alone (Vann et al., 2017) and likely delaying resistance to either herbicide mechanism of action (Green et al., 2016). However, current registrations prohibit this herbicide mixture because of volatility concerns (Anonymous, 2018a; Anonymous, 2018b). Thus, this restriction often leaves growers making glyphosate plus dicamba applications ultimately applying dicamba as the only effective mechanism of action being used to control glyphosate resistant weeds.

The use of residual herbicides and cover crops diversifying management programs have also been shown to improve weed control while reducing selection pressure on POST applied herbicides. For example, Johnson et al. (2012) observed both improved common waterhemp and giant ragweed control with the addition of PRE herbicides in a total POST system. They also documented the PRE herbicide can assist in minimizing selection pressure by reducing the number of weeds exposed to the POST herbicide application (Johnson et al., 2012). Similarly, the use of cover crops have been shown to reduce or delay weed emergence thereby reducing the number of weedy pest to be controlled with POST herbicide applications (Aulakh et al., 2012; Bunchek et al., 2020; Price et al., 2016; Wallace et al., 2019; Webster et al., 2016; Wiggins et al., 2016). Thus, the objective of this experiment was to design dicamba-based management programs that are effective and sustainable with the potential for immediate grower adoption. The influence of cover crop, PRE herbicides, and a layby post-directed (LPD) application using traditional herbicide chemistry were evaluated to determine their influence on selection pressure of dicamba applied POST in a cotton weed management program.

MATERIALS AND METHODS

During 2018 and 2019, an experiment was conducted four times in Ty Ty, GA and Jackson, TN; site characterization including soil texture, organic matter, soil pH, cereal rye biomass, and cotton planting date are provided in Table 1. Treatments were arranged in a split-plot design, with the whole plot being conventional tillage or cereal rye cover crop. For the cover crop systems, cereal rye (*Secale cereale* L.) (cv. 'Wrens Abruzzi') was planted at a seeding rate of 100 kg ha^{-1} with a grain drill (Great Plains Manufacturing, Salina, KS) in the November to December prior to cotton planting. Once the cereal rye reached a minimum height of 2 m in the spring, it was rolled with a roller crimper (I & J Manufacturing, Gordonville, PA) in the direction cotton would be planted and killed with glyphosate in preparation for planting cotton. Cotton was planted using a strip-till planter system, with a two-row planter attached to the strip-till implement to reduce planting, in GA and with a no-till planter in TN. For conventional tillage systems, bareground beds were roto-tilled making them free of weeds and debris and planted on the same day using the same planters as noted for the conservation tillage systems. Deltapine 1646 B2XF and Deltapine 1518 B2XF at 2 seeds per 20 cm were planted 1.2 cm deep in GA and TN, respectively. Cultural practices, including fertilization, insect management, plant growth management and defoliation, were conducted as recommended by the extension service in each state (Raper, 2014; Whitaker et al., 2018).

The subplot was herbicide system, with four systems evaluated: (1) no herbicide; (2) 3 sequential applications of dicamba plus glyphosate POST (0.56 + 1.12 kg ai ha^{-1}); (3) diuron plus fomesafen (0.57 + 0.17 kg ai ha^{-1}) PRE fb 3 sequential applications of dicamba plus glyphosate POST; and (4) diuron plus fomesafen PRE fb 2 applications of dicamba plus glyphosate POST fb diuron plus MSMA (0.84 + 1.38 kg ai ha^{-1}) plus crop oil concentrate (1% v/v) directed at layby. PRE applications occurred 0 to 1 d after planting, POST 1 occurring 12 to 23 d after PRE applications, POST 2 occurring 18 to 30 d after POST 1, and POST 3/LPD occurring 16-21 d after POST 2. Cotton height, weed height, and maximum weed density for each location are listed in Table 2.

Two dicamba-based programs included three dicamba POST applications following label requirements at the time the experiment was initiated. In 2019, new requirements limited dicamba to two in-season applications but continued to allow an additional burndown application equaling a potential for three applications during the season (Anonymous, 2018a; 2018b). All herbicides were applied using a CO_2 – pressurized backpack sprayer calibrated to deliver 140 L ha^{-1}. PRE and POST applications were made using 110015 TTI nozzles, while layby applications were made using Floodjet TK-VS2 nozzles (Teejet Technologies, Wheaton, IL) with spray directed toward the bottom 10 cm of the cotton plant. All residual herbicides were activated with at least 0.6 cm of rainfall or irrigation within 48 hr of application. Plots were two rows wide spaced 96 cm apart and 9 m long in TN, and four or six rows wide spaced 92 cm apart and 7.5 m long in GA.

In GA, differences in cotton stand relative to tillage system were visually evident thus stand was recorded; differences were not observed in TN and were not recorded. Emerged cotton plants were counted for the entire plot 15 d after planting in GA. Cotton heights were also collected in GA on 20 plants per plot beginning 6 d after POST 2 and were measured up to 5 d after POST 3/LPD to determine the impacts of weed competition on cotton growth. Visual injury to cotton was evaluated following each herbicide application. However, injury was less than 10% for all treatments, evaluation dates, and locations and will not be reported.

To quantify the influence cover crop, PRE herbicides, and a directed layby application had on the selection pressure of glyphosate plus dicamba applied POST, weeds were counted one day prior to each in-season herbicide application. In GA the entire plot was counted, while a representative 0.25 m^2 quadrat of each plot was counted in TN. Following the first POST application, broadleaf weeds present were separated into two categories: 1) previously treated and damaged by dicamba or 2) newly emerged, which quantifies the total number of weeds being treated with dicamba plus glyphosate but also determines the number of weeds surviving at least one dicamba plus glyphosate application with potential for additional exposure. Separating weed counts into previously damaged or newly emerged occurred at the three GA locations. From these counts, exposure to glyphosate plus dicamba over the entire season can be calculated, which can assist in determining the optimum weed management system to reduce exposure to POST herbicide options in cotton. Weeds counted throughout the season included Palmer amaranth, pitted morningglory (*Ipomea lacunosa* L.), yellow nutsedge (*Cyperus esculentus* L.), and crowfootgrass [*Dactyloctenium aegyptium* (L.) Willd.]. At the end of the season, Palmer amaranth and crowfootgrass were counted for the entire plot and subsequently cut and weighed for biomass where present in GA. Pitted morningglory and yellow nutsedge were not evaluated at the end of the season because pitted morninglory vines were desiccated by defoliation mixtures and yellow nutsedge was eliminated by a late-season fungus. Cotton was then harvested using a cotton picker for yield comparisons.

Data were subjected to ANOVA using PROC GLIMMIX in SAS, version 9.4 (SAS Institute, Cary, NC) evaluating the impact of tillage option and herbicide program on the response variables. Cotton stand and height, weed counts and biomass, and cotton yield were all set as the response variables in the model, while block and location were included as random factors. Location by treatment interactions were evaluated for all response variables, and when appropriate, data was separated by location for analysis. All weed counts were square root transformed, and weed biomass was log transformed to improve normality and homogeneity of variance prior to analysis, however all data are presented in their back-transformed values. All P values for tests of differences between lest-squares means were compared and adjusted using the Shaffer-simulated method ($\alpha = 0.05$).

RESULTS AND DISCUSSION

Cotton Stand

Cotton stand was influenced by soil temperature during emergence in GA. Two distinct environmental conditions were noted with maximum soil temperatures ranging from 30-37 C for two locations (2018 and 2019 early planted) and 40-43 C for one location (2019 late planted).

When combined across 2018 and 2019 early planted locations, cotton stand was higher with conventionally prepared soil (112,345 plants ha^{-1}) compared to cover crop treatments (94,144 plants ha^{-1}) (data not shown). Conditions at these locations were optimal for cotton germination and root development in the conventional system with maximum soil temperatures ranging from 30-37 C and minimum soil temperatures ranging from 18-23 C (McMichael and Burke, 1994; Pearson et al., 1970; Raphael et al., 2017; Snider et al., 2014). The reduction in stand with the cover crop may have been influenced by cooler soil temperatures and higher moisture levels which has been previously documented (Teasdale and Mohler, 1993). In fact, Teasdale and Mohler (1993) observed predicted soil temperature decreases of 2 to 5 C in the first five weeks following cover crop termination when 3,000 kg ha^{-1} of residue was present. Although a greater plant population was noted in conventional systems, both production practices had an adequate plant stand to maximize yield potential (Whitaker et al., 2018)

At the third GA location, maximum soil temperatures ranged from 40 to 43 C for each of the first seven days after planting in the conventional system. McMichael and Burke (1994) noted root development at 40 C was nearly half that observed at 34 C. Irrigation was implemented to preserve the crop but limitations of irrigation volume and the inability to lower soil temperatures for an extended period of time limited irrigation benefits. Due to these adverse conditions, cotton stand was significantly reduced when planted into conventional tillage (51,457 plants ha^{-1}), while cotton planted into a rye cover crop noted a higher stand (79,072 plants ha^{-1}). As mentioned earlier, cover crops can reduce soil temperatures and help preserve soil moisture improving emergence in excessively hot or dry environments (Teasdale and Mohler, 1993). Final populations in the conservation tillage systems were adequate to maximize yield potential while those in the conventional systems were low (Whitaker et al., 2018).

Cotton Heights

Results were not influenced by year or location, thus heights were combined for analysis. Since herbicide injury was transient, differences in cotton heights assist in quantifying the impact of early-season weed control on competition with the crop. Although less weeds were noted in the conservation tillage system when compared to the conventional system (Table 3), early-season weed competition was similar among tillage systems. The emerging weed population in the strip-tilled area of the conservation tillage system (10 cm on each side of the cotton plant) was similar to that observed in the respective area of the conservation tillage system leading to similar early-season weed competition on the young cotton (data not shown). In contrast, differences in herbicide systems were significant. Approximately two wks after POST 1, the tallest cotton was observed when a PRE herbicide was followed by a POST application (36 cm), where cotton treated with a POST only and cotton not treated with a herbicide were significantly shorter (25 and 26 cm, respectively) (data not shown). The weeds present in these locations (Palmer amaranth, pitted morningglory, crowfootgrass, and yellow nutsedge) are all extremely competitive with crops, competing for light, nutrients, space, and water (Zimdahl, 2004). A PRE application can be vital to reduce weed competition and maximize yield in cotton (Byrd and Coble, 1991; Crowley et al., 1978; Keeley and Thullen, 1975; Rowland et al., 1999).

Palmer amaranth

Density counts were averaged over the TN and three GA locations and was influenced by the interaction of tillage option and herbicide system when evaluated 1 d before the first POST application. Nearly 2 million plants ha^{-1} were recorded in the tilled system when no herbicide was utilized (Table 3). The cover crop alone reduced emergence 75% which is an effective approach in reducing selection pressure of POST applied herbicides (Aulakh et al., 2012;

Bunchek et al., 2020; Price et al., 2016; Wallace et al., 2019; Webster et al., 2016; Wiggins et al., 2016). The application of two effective mechanisms of action PRE, with timely rainfall or irrigation, was even more effective than the cover crop reducing the number of Palmer amaranth plants present by at least 99.7%, regardless of production system. The value of residual herbicides with a cover crop are often questioned due to the cover crop prohibiting some of the herbicide from reaching the soil (Teasdale et al., 2003). However, this study and others have documented residual herbicides in combination with a cover crop may be one of the most effective approaches for reducing selection pressure to POST applied herbicides (Bunchek et al., 2020; Wallace et al., 2019). Additionally, the cover crop had a similar influence reducing the number of plants to be controlled by PRE herbicides thereby reducing selection pressure on those herbicide tools as well.

Just prior to the second POST application, over 1.2 million plants ha^{-1} were observed in the no-herbicide conventional system (Table 4). Intra- and interspecific competition has been noted with Palmer amaranth in soybean and sweet potato [*Ipomoea batatas* (L.) Lam.], and could be why density was reduced at each application timing (Basinger et al., 2019a; 2019b). The cover crop alone or glyphosate plus dicamba POST 1 reduced the number of plants present 70 to 81% when compared to the conventional control. The cover crop was as effective as a single POST application in controlling the weed at this time. Previous research has noted suboptimal control from one application of dicamba to Palmer amaranth (Merchant et al., 2013). Although cover crops are extremely effective early in the season, herbicides are still necessary for season-long weed control (Teasdale, 1996). The PRE fb POST program, regardless of production system, reduced the number of plants treated by the POST 2 application by at least 98.5%.

Trends one d prior to POST 3 were similar, with the cover crop alone providing 54% control, and all herbicide systems providing 90% control or greater (data not shown).

With density counts taken one d prior to each POST application, the total number of Palmer amaranth exposed to dicamba plus glyphosate over the entire season within each system can be calculated. Results were influenced by the interaction of tillage option and herbicide system. The highest level of exposure was present when 3 sequential POSTs were applied in conventional tillage (2,155,409 plants ha^{-1}) (Table 5). The addition of the cover crop with this program reduced season-long exposure to dicamba plus glyphosate 65%. Although the cover crop was beneficial, the PRE application was more impactful reducing exposure over 97 and 91% in conventional and conservation tillage systems, respectively. Replacing the POST 3 application with the LPD application further reduced the number of Palmer amaranth plants treated with glyphosate plus dicamba by 38,319 plant ha^{-1} when comparing relative systems. This was a 66% reduction in exposure (18,105 vs 56,424 plants ha^{-1}) at this time (data not shown). Layby applications in cotton can provide a unique opportunity to further reduce selection pressure to POST herbicide options by utilizing additional mechanisms of action that can provide both POST and residual control of problematic weeds (Clewis et al., 2008; Price et al., 2008).

Reducing the number of plants treated with dicamba is paramount for farm sustainability; however, reducing the number of plants receiving multiple exposures over time may be even more important (Bagavathiannan and Davis, 2018; Tehranchian et al., 2017). In GA, it was determined that the number of plants ha^{-1} surviving glyphosate plus dicamba POST 1 to be treated with a second application was 204,472; about 10% of the emerged population at time of POST 1 (Table 4). The addition of a cover crop or a PRE herbicide in conjunction with the

POST 1 application reduced the number of plants previously surviving a dicamba plus glyphosate application by over 43 or 97%, respectively. At time of the final herbicide application, 35 times more Palmer amaranth had survived in the total POST program (43,506 plants ha^{-1}) receiving either one or two previous exposures to dicamba as compared to the PRE fb POST program (1,208 plant ha^{-1}). Treating the same weed population with the same mechanism of action continuously places enormous selection pressure for the development of herbicide resistance (Bagavathiannan and Davis, 2018). Therefore, reducing the number of Palmer amaranth treated with a single mechanism of action multiple times in a season reduces the likelihood of developing resistance.

Palmer amaranth plants were counted and weighed at harvest to evaluate the impact of tillage option and herbicide system on population and size over the entire season. Both end of season counts and biomass were impacted by the main effect of herbicide system. Price et al. 2016 also observed that cover crop and tillage systems had generally similar weed densities at harvest after herbicide programs were implemented. Palmer amaranth density and biomass were highest when no herbicide was used (167,641 plants ha^{-1} weighing 1,793 kg ha^{-1}) (Table 6). All herbicide systems resulted in a similar reduction in both population and biomass (102 – 847 plants ha^{-1} weighing 7 – 24 kg ha^{-1}). However, when only comparing treatments receiving herbicides, both systems receiving a PRE resulted in reduced density compared to the 3 sequential POST system (data not shown). Of special note is that even with an ideal herbicide system, including a PRE application with two effective mechanisms of action, sequential POST applications, and a layby application, Palmer amaranth was not eliminated at the end of the season.

Crowfootgrass

Density counts are combined over two GA locations and an interaction of tillage option and herbicide system was noted for the values taken one d before POST 1. The highest density of 788,759 plants $ha^{-1}$was present in conventional tillage with no herbicide (Table 3). The cover crop reduced the density 74% with the PRE herbicide being more effective at 92%. Both fomesafen and diuron have demonstrated substantial grass control when applied PRE (Gardner et al., 2006; Walker et al., 1998). The integrated system of cover crops and the PRE herbicide reduced the population nearly 95% when compared to the conventional control (Table 3). In peanuts, similar results were observed. Large crabgrass (*Digitaria sanguinalis* L.) control was 41% with a cover crop and 61% with two effective PRE herbicides, but when herbicides and cover crop were used simultaneously control was 91% (Aulakh et al., 2015).

The highest density at POST 2 was also observed in conventional tillage with no herbicide treatment (662,439 plants ha^{-1}) (Table 4). The cover crop reduced density 72%, however, 98% of a reduction was observed with the PRE fb POST herbicide system in both tillage systems. Over ½ million crowfootgrass plants ha^{-1} emerged after the POST 2 application and before the final herbicide application in conventional tillage with no herbicide, documenting the need for late-season weed control in cotton (data now shown). Previous work has demonstrated the need for late-season grass control in cotton. Even when *S*-metolachlor was applied early POST with glyphosate, late-season control of grass weeds was less than 80%, resulting in yield losses of at least 23% (Clewis et al., 2006). Even after continual grass emergence, density counts at time of the final herbicide application were 49% less with the cover crop when averaged over herbicide systems and were 98% less with herbicide systems, regardless of tillage system, when compared to no herbicides (data not shown).

At harvest, crowfootgrass was counted and weighed to determine the impact of tillage option and herbicide system on density over the entire season. Both counts and biomass were only impacted by the main effect of herbicide system. Density at harvest was highest when no herbicide was used (2,636,244 plants ha^{-1}), while adding any herbicide system resulted in a reduction over 98% (Table 6). Similar to counts, biomass was highest when no herbicide was used (1,817.2 kg ha^{-1}) but differences among herbicide systems was observed. A total POST program and the PRE fb three POST applications accumulated 18.8 and 5.2 times more biomass than the standard system of a PRE fb sequential POST and a directed layby (Table 6). Residual activity from diuron reducing late-emerging plants was likely part of the difference. Clewis et al. (2008) also observed improved grass control when directed layby applications were used compared to POST only systems or when no layby was applied.

Yellow Nutsedge

Averaged over the two GA locations where nutsedge was present, an interaction of tillage option and herbicide system was noted one day prior to the first POST application (Table 3). The highest yellow nutsedge density was present with conventional tillage without herbicides (1,320,437 plants ha^{-1}). The addition of the rye cover crop reduced yellow nutsedge populations 68% (Table 3). When yellow nutsedge control was evaluated in peanut, no differences were noted between conventional tillage treatments compared to when a cover crop was used which the authors attributed to low biomass levels accrued and soil moisture (Aulakh et al., 2015). The PRE herbicide treatment reduced the nutsedge population 87% just prior to the first glyphosate plus dicamba application and was likely a result from fomesafen activity (Table 3). Previous research in multiple cropping systems has demonstrated that the residual activity of fomesafen can effectively control of yellow nutsedge (Boyd, 2015; Grichar,1992; Reed et al., 2016).

Similar to early-season observations, density counts at time of POST 2 noted the highest yellow nutsedge density was present when no herbicide was used in conjunction with conventional tillage (3,209,930 plants ha^{-1}) (Table 4). The addition of a cover crop alone, herbicides alone, or cover crop plus herbicide reduced the population 78 to 90%. At POST 3, tillage practices had no impact but herbicide systems continue to reduce the population at least 76% (data not shown). All treatments that received herbicide applications included POST applications of glyphosate in tank-mix with dicamba. Previous research by Burke et al. (2008) noted significant reductions in shoot and root/tuber dry weights resulting from applications of glyphosate. The utilization of glyphosate to reduce tuber production in a weed management system plays a large part in long-term management of nutsedge species (Burke et al., 2008; Reddy and Bryson, 2009; Webster et al., 2008).

Pitted Morningglory

PRE herbicides did not reduce the morningglory population at any of the three GA locations where the weed was present (data not shown). Previous research has demonstrated that neither fomesafen nor diuron applied PRE effectively control morningglory (Gardner et al., 2006; Osborne et al., 2003). Glyphosate plus dicamba POST and the LPD application provided complete control of emerged morningglory (data not shown). However, the weed continued to emerge after each application which has been documented in morningglory species (Norsworthy and Oliveira, 2007; Oliveira and Norsworthy, 2006; Singh et al., 2012). Interestingly, at the location with the highest morningglory density (426,069 plants ha^{-1}), treatments with a cover crop noted a 71% reduction in morningglory density at the time of POST 1 compared to conventionally tilled treatments (data not shown). However, the cover crop was not beneficial at later evaluations nor was it beneficial during any evaluation at the other locations. Previous research has noted little benefit from a rye cover crop with respect to morningglory control (Koger et al., 2002).

Cotton Yield

Cotton yield, pooled over locations, was influenced by the main effect of herbicide system and the main effect of tillage option. With respect to herbicide system, seed cotton yield was highest when a PRE application was utilized (4,081 – 4,198 kg ha^{-1}) (Table 7). Solely relying on POST herbicides for weed control noted a reduction in seed cotton yield of 14%, while not using an herbicide resulted in a 95 to 96% yield loss. Previous research on the weed-free period of cotton has demonstrated that an 8-week weed free period should result in maximum cotton yields (Buchanan and Burns, 1970; Tursun et al., 2016). The use of a PRE application in this study followed by sequential POST applications allowed for minimal weed competition from planting through harvest. With respect to tillage option, cotton grown with a cover crop yielded higher than cotton grown in conventional tillage (3,226 and 2,761 kg ha^{-1}, respectively). Although stand was reduced in cover crop treatments at two locations, cotton has an amazing ability to compensate for gaps in stand (Hasnam, 1985). Previous research has observed increased yields from cotton grown in a cover crop, demonstrating benefits outside of just weed control. Price et al. (2012) demonstrated yield benefits in early planted cover crop treatments compared to conventional tillage in two out of three years, which resulted in greater economic returns. Price et al. (2016) also noted higher yields with cover crop treatments compared to conventional tillage. Previous research has demonstrated many benefits to utilizing cover crops including soil moisture preservation, improved water infiltration, reduced erosion and runoff and reduced thrips pressure during early-season (Mirsky et al., 2012; Knight et al., 2017; Teasdale, 1996). Many of these benefits could have factored into the increased yield observed in this experiment.

CONCLUSIONS

Reducing the number of weeds, especially Palmer amaranth, that farmers need to control with POST herbicides will likely improve farm sustainability as a result of having less herbicide resistance. The data presented herein demonstrates cover crops reduced the number of Palmer amaranth and crowfootgrass plants present from cotton emergence through the final herbicide application by 49 to 75% thereby reducing selection pressure for both PRE and POST herbicide applications. PRE herbicides were more effective than the cover crop reducing Palmer amaranth, crowfootgrass, and nutsedge plants to be controlled by POST herbicides by 77 to 99% but a combination of the cover crop and PRE herbicides was the more consistently effective option. Replacing the third POST application with a LPD application further reduced selection pressure to the POST herbicides, although much less than cover crops or PRE herbicides. Additionally, from an agronomic standpoint, a complete herbicide program improved cotton growth, development, and ultimately yield at the end of the season. Conservation tillage systems also noted higher cotton yields due to the many benefits associated with cover crop use.

ACKNOWLEDGMENTS

The authors thank Cotton Incorporated and the Georgia Cotton Commission for their partial support of this research via cooperative research agreements. The authors would like to thank Tim Richards and Jenna Vance for their technical assistance. Furthermore, the authors would like to acknowledge the hard work and dedication of the student workers present at the time of these studies. No conflicts of interest have been declared.

REFERENCES

Anonymous. 2018a. Engenia® herbicide product label. EPA Reg. No. 7969-345. BASF Corporation, Research Triangle Park, NC.

Anonymous. 2018b. Xtendimax® with VaporGrip Technology product label. EPA Reg. No. 524-617. Bayer CropScience, St. Louis, MO.

Aulakh, J.S., A.J. Price, S.F. Enloe, E. van Santen, G. Wehtje, and M.G. Patterson. 2012. Integrated Palmer amaranth management in glufosinate-resistant cotton: I. Soil-Inversion, high-residue cover crops, and herbicide regimes. Agronomy 2:295-311.

Aulakh, J.S., M. Saini, A.J. Price, W.H. Faircloth, E. van Santen, G.R. Wehtje, and J.A. Kelton. 2015. Herbicide and rye cover crop residue integration affect weed control and yield in strip-tillage peanut. Peanut Sci. 42:30-38.

Bagavathiannan, M.V., and A.S. Davis. 2018. An ecological perspective on managing weeds during the great selection for herbicide resistance. Pest Manag. Sci. 74:2277-2286.

Barnett, K.A., T.C. Mueller, and L.E. Steckel. 2013. Glyphosate-resistant giant ragweed (*Ambrosia trifida*) control with glufosinate or fomesafen combined with growth regulator herbicides. Weed Technol. 27:454-458.

Basinger, N.T., K.M. Jennings, D.W. Monks, D.L. Jordan, W.J. Everman, E.L. Hestir, M.D. Waldschmidt, S.C. Smith, and C. Brownie. 2019a. Interspecific and intraspecific interference of Palmer amaranth (*Amaranthus palmeri*) and large crabgrass (*Digitaria sanguinalis*) in sweetpotato. Weed Sci. 67:426-432.

Basinger, N.T., K.M. Jennings, D.W. Monks, D.L. Jordan, W.J. Everman, E.L. Hestir, M.T. Bertucci, and C. Brownie. 2019b. Large crabgrass (*Digitaria sanguinalis*) and Palmer amaranth (*Amaranthus palmeri*) intraspecific and interspecific interference in soybean. Weed Sci. 67:649-656.

Bradshaw, L.D., S.R. Padgette, S.L. Kimball, and B.H. Wells. 1997. Perspectives on glyphosate resistance. Weed Technol. 11:189-198.

Boyd, N.S. 2015. Evaluation of preemergence herbicides for purple nutsedge (*Cyperus rotundus*) control in tomato. Weed Technol. 29:480-487.

Buchanan, G.A., and E.R. Burns. 1970. Influence of weed competition in cotton. Weed Sci. 18:149-154.

Bunchek, J.M., J.M. Wallace, W.S. Curran, D.A. Mortensen, M.J. VanGessel, and B.A. Scott. 2020. Alternative performance targets for integrating cover crops as a proactive herbicide-resistance management tool. Weed Sci. doi:10.1017/wsc.2020.49.

Burke, I.C., S.C. Troxler, J.W. Wilcut, and W.D. Smith. 2008. Purple and yellow nutsedge (*Cyperus rotundus* and *C. esculentus*) response to postemergence herbicides in cotton. Weed Technol. 22:615-621.

Busi, R., M.M Vila-Aiub, H.J. Beckie, T.A. Gaines, D.E. Goggin, S.S. Kaundun, M. Lacoste, P. Neve, S.J. Nissen, J.K. Norsworthy, M. Renton, D.L. Shaner, P.J. Tranel, T. Wright, Q. Yu, S.B. Powles. 2013. Herbicide-resistant weeds: from research and knowledge to future needs. Evol. Appl. 6:1218-1221.

Byrd, J.D., and H.D. Coble. 1991. Interference of selected weeds in cotton (*Gossypium hirsutum*). Weed Technol. 5:263-269.

Cahoon, C.W., A.C. York, D.L. Jordan, W.J. Everman, R.W. Seagroves, A.S. Culpepper, and P.M. Eure. 2015. Palmer amaranth management in dicamba-resistant cotton. Weed Technol. 29:758-770.

Clewis, S.B., D.K. Miller, C.H. Koger, T.A. Baughman, A.J. Price, D. Porterfield, and J.W. Wilcut. 2008. Weed management and crop response with glyphosate, *S*-metolachlor, trifloxysulfuron, prometryn, and MSMA in glyphosate-resistant cotton. Weed Technol. 22:160-167.

Clewis, S.B., J.W. Wilcut, and D. Porterfield. 2006. Weed management with *S*-metolachlor and glyphosate mixtures in glyphosate-resistant strip- and conventional-tillage cotton (*Gossypium hirsutum* L.). Weed Technol. 20:232-241.

Cranston, H.J., A.J. Kern, J.L. Hackett, E.K. Miller, B.D. Maxwell, and W.E. Dyer. 2001. Dicamba resistance in kochia. Weed Sci. 49:164-170.

Crowley, R.H., and G.A. Buchanan. 1978. Competition of four morningglory (*Ipomoea* spp.) species with cotton (*Gossypium hirsutum*). Weed Sci. 26:484-488.

Culpepper, A.S. 2006. Glyphosate-induced weed shifts. Weed Technol. 20:277-281.

Culpepper, A.S., T.L. Grey, W.K. Vencill, J.M. Kichler, T.M. Webster, S.M. Brown, A.C. York, J.W. Davis, and W.W. Hanna. 2006. Glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) confirmed in Georgia. Weed Sci. 54:620-626.

Everman, W.J., S.B. Clewis, A.C. York, and J.W. Wilcut. 2009. Weed control and yield with flumioxazin, fomesafen, and *S*-metolachlor systems for glufosinate-resistant cotton residual weed management. Weed Technol. 23:391-397.

Gaines, T.A., E.L. Patterson, P. Neve. 2019. Molecular mechanisms of adaptive evolution revealed by global selection for glyphosate resistance. New Phytol. 223:1770-1775.

Gardner, A.P., A.C. York, D.L. Jordan, and D.W. Monks. 2006. Management of annual grasses and *Amaranthus* spp. in glufosinate-resistant cotton. J. Cotton. Sci. 10:328-338.

Green, J.M. 2009. Evolution of glyphosate-resistant crop technology. Weed Sci. 57:108-117.

Green, J.M., and M.D.K. Owen. 2011. Herbicide-resistant crops: utilities and limitations for herbicide-resistant weed management. J. Agric. Food. Chem. 59:5819-5829.

Gressel, J., A.J. Gassmann, and M.D.K. Owen. 2016. How well will stacked transgenic pest/herbicide resistances delay pests from evolving resistance? Pest Manag. Sci. 73:22-34.

Grichar, W.J. 1992. Yellow nutsedge (*Cyperus esculentus*) control in peanuts (*Arachis hypogaea*). Weed Technol. 6:108-112.

Gustafson, D.I. 2008. Sustainable use of glyphosate in North American cropping systems. Pest Manag. Sci. 64:409-416.

Hasnam. 1985. Plant and yield responses to skips in upland cotton. Indones. J. Crop. Sci. 1:29-42.

Heap, I. 2014. Global perspective of herbicide-resistant weeds. Pest. Manag. Sci. 70:1306-1315.

Johnson, G., F. Breitenbach, L. Behnken, R. Miller, T. Hoverstad, and J. Gunsolus. 2012. Comparison of herbicide tactics to minimize species shifts and selection pressure in glyphosate-resistant soybean. Weed Technol. 26:189-194.

Jones, M.A., and C.E. Snipes. 1999. Tolerance of transgenic cotton to topical applications of glyphosate. J. Cotton Sci. 3:19-26.

Keeley, P.E., and R.J. Thullen. 1975. Influence of yellow nutsedge competition on furrow-irrigated cotton. Weed Sci. 23:171-175.

Knight, I.A., G.C. Rains, A.K. Culbreath, and M.D. Toews. 2017. Thrips counts and disease incidence in response to reflective particle films and conservation tillage in cotton and peanut cropping systems. Entomol. Exp. Appl. 162:19–29.

Koger, C.H., K.N. Reddy, and D.R. Shaw. 2002. Effects of rye cover crop residue and herbicides on weed control in narrow and wide row soybean planting systems. Weed Bio. Manag. 2:216-224.

Kruger, G.R., V.M. Davis, S.C. Weller, and W.G. Johnson. 2010. Control of horseweed (*Conyza canadensis*) with growth regulator herbicides. Weed Technol. 24:425-429.

Leon, R.G., J.A. Ferrell, and B.A. Sellers. 2016. Seed production and control of sicklepod (*Senna obtusifolia*) and pitted morningglory (*Ipomoea lacunosa*) with 2,4-D, dicamba, and glyphosate combinations. Weed Technol. 30:76-84.

Manuchehri, M.R., P.A. Dotray, and J.W. Keeling. 2017. Enlist™ weed control systems for Palmer amaranth management in Texas high plains cotton. Weed Technol. 31:793-798.

McElroy, J.S. 2014. Vavilovian Mimicry: Nikolai Vavilov and his little-known impact on weed science. Weed Sci. 62:207-216.

McMichael, B.L. and J.J. Burke. 1994. Metabolic activity of cotton roots in response to temperature. Environmental and Experimental Botany 34:201-206.

Merchant, R.M., L.M. Sosnoskie, A.S. Culpepper, L.E. Steckel, A.C. York, L.B. Braxton, and J.C. Ford. 2013. Weed response to 2,4-D, 2,4-DB, and dicamba applied alone or with glufosinate. J. Cotton Sci. 17:212-218.

Meyer, C.J., J.K. Norsworthy, B.G. Young, L.E. Steckel, K.W. Bradley, W.G. Johnson, M.M. Loux, V.M. Davis, G.R. Kruger, M.T. Bararpour, J.T. Ikley, D.J. Spaunhorst, and T.R. Butts. 2015. Herbicide program approaches for managing glyphosate-resistant Palmer amaranth and waterhemp in future soybean-trait technologies. Weed Technol. 29:716-729.

Mirsky, S.B., M.R. Ryan, W.S. Curran, J.R. Teasdale, J. Maul, J.T. Spargo, J. Moyer, A.M. Grantham, D. Weber, T.R. Way, and G.G. Camargo. 2012. Conservation tillage issues: cover crop-based organic rotational no-till grain production in the mid-Atlantic region, USA. Renew. Agr. Food Syst. 27:31–40.

Norsworthy, J.K., and M.J. Oliveira. 2007. Role of light quality and temperature on pitted morningglory (*Ipomoea lacunosa*) germination with after-ripening. Weed Sci. 55:111-118.

Oliveira, M.J., and J.K. Norsworthy. 2006. Pitted morningglory (*Ipomoea lacunosa*) germination and emergence as affected by environmental factors and seeding depth. Weed Sci. 54:910-916.

Osborne, T.S., J.W. Keeling, and P.A. Dotray. 2003. Pyrithiobac combinations control red morningglory (*Ipomoea coccinea*) and devil's-claw (*Proboscidea louisianica*) in non-transgenic cotton (*Gossypium hirsutum*). Texas J. Agric. Nat. Resour. 16:15-23.

Pearson, R.W., L.F. Ratliff, and H.M. Taylor. 1970. Effect of soil temperature, strength, and pH on cotton seedling root elongation. Agron. J. 62:243-246.

Price, A.J., K.S. Balkcom, L.M. Duzy, and J.A. Kelton. 2012. Herbicide and cover crop residue integration for *Amaranthus* control in conservation agriculture cotton and implications for resistance management. Weed Technol. 26:490–498.

Price, A.J., C.H. Koger, J.W. Wilcut, D. Miller, and E. van Santen. 2008. Efficacy of residual and non-residual herbicides used in cotton production systems when applied with glyphosate, glufosinate, or MSMA. Weed Technol. 22:459-466.

Price, A.J., C.D. Monks, A.S. Culpepper, L.M. Duzy, J.A. Kelton, M.W. Marshall, L.E. Steckel, L.M. Sosnoskie, and R.L. Nichols. 2016. High-residue cover crops alone or with strategic tillage to manage glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) in southeastern cotton (*Gossypium hirsutum*). J. Soil Water Conserv. 71:1–11.

Raper, T. 2014. 2014 Tennessee Cotton Quick Facts. Knoxville, TN: University of Tennessee. Publication No. W319. 2 p

Raphael, J.P.A., B. Gazola, J.G.S. Nunes, G.C. Macedo, and C.A. Rosolem. 2017. Cotton germination and emergence under high diurnal temperatures. Crop Sci. 57:2761-2769.

Reddy, K.N., and C.T. Bryson. 2009. In-crop and autumn-applied glyphosate reduced purple nutsedge (*Cyperus rotundus*) density in no-till glyphosate-resistant corn and soybean. Weed Technol. 23:384-390.

Reed, T.V., N.S. Boyd, and P.J. Dittmar. 2016. Application timing influences purple nutsedge (*Cyperus rotundus*) and yellow nutsedge (*Cyperus esculentus*) susceptibility to EPTC and fomesafen. Weed Technol. 30:743-750.

Rowland, M.W., D.S. Murray, and L.M. Verhalen. 1999. Full-season Palmer amaranth (*Amaranthus palmeri*) interference with cotton (*Gossypium hirsutum*). Weed Sci. 47:305-309.

Singh, M., A.H.M. Ramirez, S.D. Sharma SD, and A.J. Jhala. 2012. Factors affecting the germination of tall morningglory (*Ipomea purpurea*). Weed Sci. 60:64-68.

Snider, J.L., G.D. Collins, J. Whitaker, K.D. Chapman, P. Horn, and T.L. Grey. 2014. Seed size and oil content are key determinants of seedling vigor in *Gossypium hirsutum*. J. Cotton Sci. 18:1-9.

Steckel, L. 2020. Dicamba-resistant Palmer amaranth in Tennessee: Stewardship even more important. https://news.utcrops.com/2020/07/dicamba-resistant-palmer-amaranth-in-tennessee-stewardship-even-more-important/ (accessed 6 Sept. 2020).

Sosnoskie, L.M., and A.S. Culpepper. 2014. Glyphosate-resistant Palmer amaranth increases herbicide use, tillage, and hand-weeding in Georgia cotton. Weed Sci. 62:393-402.

Teasdale, J.R. 1996. Contribution of cover crops to weed management in sustainable agriculture systems. J. Prod. Agric. 9:431–479.

Teasdale, J.R., and C.L. Mohler. 1993. Light transmittance, soil temperature, and soil moisture under residue of hairy vetch and rye. Agron. J. 85:673–680.

Teasdale, J.R., D.R. Shelton, A.M. Sadeghi, and A.R. Isensee. 2003. Influence of hairy vetch residue on atrazine and metolachlor solution concentration and weed emergence. Weed Sci. 51:628-634.

Tehranchian, P., J.K. Norsworthy, S. Powles, M.T. Bararpour, M.V. Bagavathiannan, T. Barber, and R.C. Scott. 2017. Recurrent sublethal-dose selection for reduced susceptibility of Palmer amaranth to dicamba. Weed Sci. 65:206-212.

Tursun, N., A. Datta, S. Budak, Z. Kantarci, and S.Z. Knezevic. 2016. Row spacing impacts the critical period for weed control in cotton (*Gossypium hirsutum*). Phytoparasitica 44:139-149.

[USDA AMS] United States Department of Agriculture, Agricultural Marketing Service. 2019. Cotton varieties planted: 2019 crop. < https://www.ams.usda.gov/mnreports/cnavar.pdf> Accessed: September 12, 2019.

[USDA NASS] United States Department of Agriculture. 2019. National Agricultural Statistics Service. <nass.usda.gov/index.php> Accessed: September 12, 2019.

VanGessel, M.J. 2001. Glyphosate-resistant horseweed from Delaware. Weed Sci. 49:703-705.

Vann, R.A., A.C. York, C.W. Cahoon Jr., T.B. Buck, M.C. Askew, and R.W. Seagroves. 2017. Glufosinate plus dicamba for rescue Palmer amaranth control in XtendFlex™ Cotton. Weed Technol. 31:666-674.

Walker, R.H., G. Wehtje, and J.S. Richburg III. 1998. Interference and control of large crabgrass (*Digitaria sanguinalis*) and southern sandbur (*Cenchrus echinatus*) in forage bermudagrass (*Cynodon dactylon*). Weed Technol. 12:707-711.

Wallace, J.M., W.S. Curran, and D.A. Mortensen. 2019. Cover crop effects on horseweed (*Erigeron canadensis*) density and size inequality at the time of herbicide exposure. Weed Sci. 67:327-338.

Whitaker, J., S. Culpepper, M. Freeman, G. Harris, B. Kemerait, C. Perry, W. Porter, P. Roberts, Y. Liu, and A. Smith. 2018. 2019 Georgia Cotton Production Guide. Athens, GA: The University of Georgia. 146 p.

Webster, T.M., T.L. Grey, J.W. Davis, and A.S. Culpepper. 2008. Glyphosate hinders purple nutsedge (*Cyperus rotundus*) and yellow nutsedge (*Cyperus esculentus*) tuber production. Weed Sci. 56:735-742.

Webster, T.M., and R.L. Nichols. 2012. Changes in the prevalence of weed species in the major agronomic crops of the southern United States: 1994/1995 to 2008/2009. Weed Sci. 60:145-157.

Webster, T.M., D.B. Simmons, A.S. Culpepper, T.L. Grey, D.C. Bridges, and B.T. Scully. 2016. Factors affecting potential for Palmer amaranth (*Amaranthus palmeri*) suppression by winter rye in Georgia, USA. Field Crops Res. 192:103-109.

Wiggins, M.S., R.M. Hayes, and L.E. Steckel. 2016. Evaluating cover crops and herbicides for glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) control in cotton. Weed Technol. 30:415-422.

Young, B.G. 2006. Changes in herbicide use patterns and production practices resulting from glyphosate-resistant crops. Weed Technol. 20:301-307.

Zimdahl, R.L. 2004. Weed-crop competition: a review. Ames, IA: Blackwell Publishing. 229 p.

Ziska, L.H., Blumenthal, D.M., and S.J. Franks. 2019. Understanding the nexus of rising CO_2, climate change, and evolution in weed biology. Invasive Plant Sci. Manag. 12:79-88.

Table 1. Soil characteristics, cover crop biomass level, and planting dates for each experiment.

Year	Site	Soil texture	Organic matter	Soil pH	Cereal rye biomass	Planting date
		% sand, silt, clay	%		kg ha^{-1}	
2018	Jackson, TN	22, 49, 29	1.4	6.6	3,651	May 10
2018	Ty Ty, GA	85, 10, 5	0.65	6.2	6,019	May 16
2019	Ty Ty, GA	84, 14, 2	0.64	5.8	2,306	May 14
2019	Ty Ty, GA	88, 10, 2	0.52	6.7	1,575	May 23

Table 2. Cotton and weed size at each application, and maximum weed population by location.

Location	Year	Application	Cotton Heights	Palmer amaranth		Pitted Morningglory		Crowfootgrass		Yellow Nutsedge	
				Height	Max. pop.[a]	Height[c]	Max. pop.[a,c]	Height[c]	Max. pop.[a,c]	Height[c]	Max. pop.[a,c]
			cm	cm	plants ha^{-1}	cm	plants ha^{-1}	cm	plants ha^{-1}	cm	plants ha^{-1}
Jackson, TN	2018	POST 1[a]	25	10	125,000	-	-	-	-	-	-
		POST 2[a]	51	8		-		-		-	
		POST 3/LPD[a]	60	5		-		-		-	
Ty Ty, GA	2018	POST 1	13	18	3,553,444	13	426,069	-	-	-	-
		POST 2	36	13		0		-		-	
		POST 3/LPD	51	13		10		-		-	
Ty Ty, GA	2019-1[b]	POST 1	20	20	7,316,338	5	47,819	20	1,075,932	40	552,378
		POST 2	51	20		5		20		26	
		POST 3/LPD	71	15		10		10		15	
Ty Ty, GA	2019-2[b]	POST 1	25	46	1,154,834	13	12,792	25	914,542	36	2,312,449
		POST 2	51	28		8		18		23	
		POST 3/LPD	79	20		8		10		15	

[a]Abbreviations: POST 1, Postemergence Application 1; POST 2, Postemergence Application 2; POST 3/LPD, Postemergence Application 3 or Layby Post-directed; Max. pop., Maximum population.

[b]Ty Ty, GA locations in 2019 were planted at different times. 2019-1 is the first planting date, while 2019-2 is the second planting date.

[c]If a "-" is present under a weed for a specific location, then that weed was not evaluated at that location.

Table 3. Weed counts one d before POST 1[a] as influenced by the interaction of tillage system and the use of a preemergence herbicide.

Tillage option	Herbicide system[a]	Palmer amaranth[b]		Crowfootgrass[b]		Yellow nutsedge[b]	
		no. ha^{-1}					
Conventional	None	1,961,175	a	788,759	a	1,320,437	a
	PRE	3,717	c	62,349	c	176,679	b
Cover crop	None	480,869	b	206,276	b	417,827	b
	PRE	1,524	c	42,974	c	300,793	b

[a]Abbreviations: PRE, preemergence; POST 1, first topical application.

[b]Data averaged over four locations for Palmer amaranth and two locations for crowfootgrass and yellow nutsedge.

Means within a column followed by a different letter are significantly different (α=0.05).

Table 4. Weed density evaluated one d before POST 2 as influenced by tillage and herbicide system.[a]

Tillage option	Herbicide system[a,b]	Palmer amaranth Total[c,e,f]		Palmer amaranth Survived[d,f]		Crowfootgrass[c,e,f] Total		Yellow nutsedge[c,e,f] Total	
		no. ha^{-1}							
Conventional	None	1,208,924	a	-		662,439	a	3,209,930	a
	POST only	227,191	bc	204,472	a	67,644	bc	293,074	b
	PRE fb POST	9,972	d	5,272	c	5,620	c	311,837	b
Cover crop	None	368,396	b	-		184,796	b	711,409	b
	POST only	127,882	cd	116,035	b	48,389	bc	514,711	b
	PRE fb POST	17,859	d	4,701	c	10,050	c	348,527	b

[a]Abbreviations: POST 2, second topical application; POST, postemergence; PRE, preemergence.

[b]The POST only herbicide system had received one application of dicamba plus glyphosate; PRE fb POST systems had received diuron plus fomesafen at planting, followed by dicamba plus glyphosate at POST 1.

[c]Total density present for each treatment.

[d]Palmer amaranth surviving the previous application of glyphosate + dicamba at the 3 GA locations; "-" designates systems where dicamba was not applied.

[e]Data averaged over four locations for Palmer amaranth and two locations for crowfootgrass and yellow nutsedge.

[f]Means within a column followed by a different letter are significantly different (α=0.05).

Table 5. Palmer amaranth exposure to dicamba plus glyphosate over the entire season as influenced by tillage and herbicide system.

Tillage option	Herbicide system	Palmer amaranth exposed[a]	
		no. ha^{-1}	
Conventional	3 POSTs[b]	2,155,409	a
	PRE fb 3 POSTs[b]	47,355	c
	PRE fb 2 POSTs fb LPD[b]	17,181	c
Cover crop	3 POSTs	744,670	b
	PRE fb 3 POSTs	66,287	c
	PRE fb 2 POSTs fb LPD	19,053	c

[a]Data are averaged over four locations. Means within a column followed by a different letter are significantly different (α=0.05).

[b]Abbreviations: POST, postemergence; PRE, preemergence; LPD, layby post-directed.

Table 6. Palmer amaranth and crowfootgrass density and biomass at harvest as influenced by herbicide system.

	Palmer amaranth[a,b]				Crowfootgrass[a,b]			
	Density		Biomass		Density		Biomass	
Herbicide system	no. ha^{-1}		kg ha^{-1}		no. ha^{-1}		kg ha^{-1}	
None	167,641	a	1,793	a	2,636,244	a	1,817.2	a
3 POSTs[c]	847	b	24	b	27,275	b	17.0	b
PRE fb 3 POSTs[c]	184	b	7	b	19,929	b	4.7	c
PRE fb 2 POSTs fb LPD[c]	102	b	8	b	2,053	b	0.9	d

[a]Palmer amaranth data averaged over four locations and crowfootgrass data averaged over two locations. Means within a column followed by a different letter are significantly different (α=0.05).

[b]Data are averaged over tillage option.

[c]Abbreviations: POST, postemergence; PRE, preemergence; LPD, layby post-directed.

Table 7. Cotton yield as influenced by the main effects of herbicide system and tillage.

	Seed cotton yield[a]	
Herbicide system[b,d]	kg ha^{-1}	
None	173	c
3 POSTs	3,521	b
PRE fb 3 POSTs	4,081	a
PRE fb 2 POSTs fb LPD	4,198	a
Tillage option[c]		
Conventional	2,761	b
Cover crop	3,226	a

[a]Data are averaged over four locations. Means within a column followed by a different letter are significantly different (α=0.05).

[b]Data averaged over tillage option.

[c]Data averaged over herbicide system.

[d]Abbreviations: POST, postemergence; PRE, premergence; LPD, layby post-directed.